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Novel Single Tuned Harmonic Filter not Affecting Fundamental Power Factor

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Abstract

In this paper, a novel single-tuned harmonic filter has been proposed, which can remove harmonics with the fundamental power factor unchanged. It can be applied to filter the harmonics made by a load whose fundamental power factor is 1 or capacitive. An example of such loads is a single-phase rectifier with a capacitor. The novel single-tuned harmonic filter has an LC branch whose resonance frequency is the same as the fundamental frequency, thus it does not pass the fundamental current and does not change the fundamental power factor. It has been discussed how to obtain the optimal filtering effect while considering the variation of parameters of the filter elements. Through simulations on the single-phase rectifier with a capacitor, it has been proved that the filter proposed in this paper does not affect the fundamental power factor and decreases the transmission loss by 0.53 times compared to the conventional one while providing the same filtering effect.

Keywords

Passive Harmonic Filter, Single Tuned Harmonic Filter, Fundamental Power Factor

1. Introduction

A single-tuned harmonic filter is a passive harmonic filter widely used to eliminate harmonics in power systems [1-9].

The single-tuned harmonic filter and its characteristic curve are given in Fig. 1.

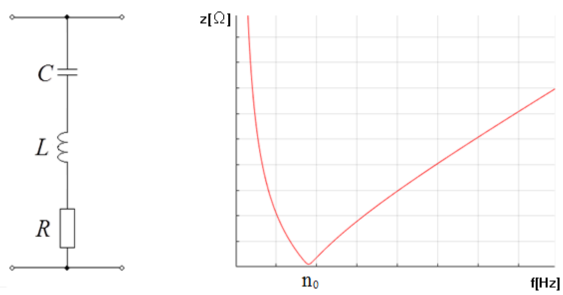

Figure 1. The single-tuned harmonic filter and its characteristic curve.

In a single-tuned harmonic filter, the values of L and C are determined so that they can be in resonance at the n_0-th order harmonic frequency to be removed.

Minimizing the impedance of the filter at the n_0-th order harmonic frequency makes the harmonic voltage produced by the harmonic current generated by the non-linear load a minimum.

This is the principle of harmonic filtering in a single-tuned harmonic filter.

While eliminating the corresponding harmonic, affects the fundamental power factor. That is why a single-tuned harmonic filter itself is capacitive at the fundamental frequency.

Up to now, the most of power systems have been inductive at the fundamental frequency, so in general, its capacitive characteristics played a positive role in raising the power factor of the power system.

But nowadays, with the widespread use of power electronic devices, there are more and more loads that are non-inductive at the fundamental frequency in the power system.

One of them is the single-phase rectifier with capacitors.

Because of its simplicity, it is widely used in the relatively small capacity of power electronic devices such as TVs, LED lamps, computers, and so on.

Fig. 2 shows its circuit and input current waveform.

It can be seen in Fig. 2 that the fundamental current is not inductive, but capacitive a little.

Suppose there is an official building whose main electrical loads are LED lamps, computers, and TVs that have the rectifiers described above.

They should produce much harmonic current and harmonic voltage.

In this case, using the conventional single-tuned harmonic filter results in the decrement of the fundamental power factor in the capacitive direction and the increment of transmission loss.

In order to overcome these disadvantages, it is necessary to find out a new type of filter that eliminates harmonics but does not influence the fundamental power factor.

It can be realized when the fundamental current does not flow through the filter and it will be possible by using an LC parallel branch whose resonance is at the fundamental frequency.

This paper describes a new type of single-tuned harmonic filter that does only the harmonic-filtering performance while not flowing the fundamental current through it and not changing the fundamental power factor.

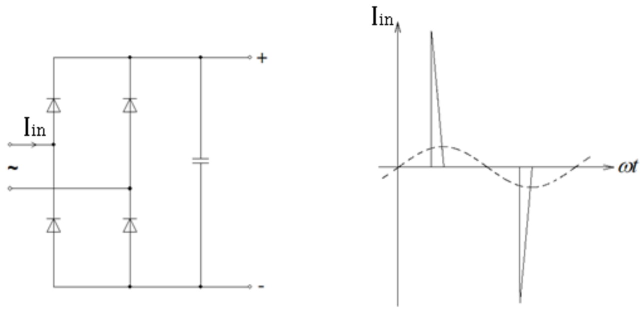

Figure 2. The single-phase rectifier with a capacitor and its input current waveform.

2. Structure of novel harmonic filter and its characteristics.

1) Structure and main characteristics.

In practice there are many loads that generate a lot of harmonics and their fundamental power factors are nearly 1 or capacitive.

Those are LED lamps, TVs, computers, and so on.

Of course, there are no problems in those devices with the PFC (Power Factor Correction) function, but now the products without the PFC function are also widely used because of their simplicities and low costs.

If the ratio of such a load to total ones is low, then any problems do not exist owing to small amounts of harmonics. However, in places like official buildings where such loads mentioned above are main loads, the problem becomes serious.

When using a single-tuned harmonic filter to eliminate harmonics in such a place, it is necessary to pay attention to the decrement of the fundamental power factor.

To avoid the power factor decrement, the fundamental current should not pass through the filter, which means that any circuit element whose impedance is infinite should be linked serially to the filter.

That is just the LC parallel branching resonance at the fundamental frequency, and in this case, the rest of the parameters should be determined so that the filter could act as a single-tuned harmonic filter.

Such a novel single-tuned harmonic filter is given in Fig. 3.

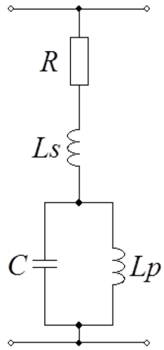

Figure 3. Novel single-tuned harmonic filter.

In Fig. 3, R is the equivalent resistance, which is determined as the sum of the resistances of the serial reactor and linking wires and some others; Ls is the reactance of the serial reactor, C and Lp are the capacitance and reactance of LC parallel branch, respectively.

In this type of filter, the resistance of $\mathbf{L_p}$ is neglected, because it is too little compared to the reactance of $\mathbf{L_p}$.

From the condition of parallel resonance,

$$\omega L_p = \frac{1}{\omega C} \tag{1}$$

where $\boldsymbol{\omega}$ is the angle frequency of the power system.

Thus

$$L_p = \frac{1}{\omega^2 C} \tag{2}$$

Provided that the impedance of the filter should be zero at the $\mathbf{n_0}$-th order harmonic frequency, the following equation can be written.

$$jn_0\omega L_s + \frac{jn_0\omega L_p \cdot (-j\frac{1}{n_0\omega c})}{jn_0\omega L_p - j\frac{1}{n_0\omega c}} = 0 \tag{3}$$

where $\mathbf{n_0}$ is harmonic order to be removed.

Arranging equation (3),

$$L_s = \frac{L_p}{{n_0}^2 - 1} = \frac{1}{{n_0}^2 - 1} \cdot \frac{1}{\omega^2 c} \tag{4}$$

The n-th harmonic impedance of the filter is

$$Z_n = R + jX_n = R + jn\omega L_s + \frac{jn\omega L_p \cdot (-j\frac{1}{n\omega c})}{jn\omega L_p - j\frac{1}{n\omega c}} \tag{5}$$

From equations (2), (4) and (5), the reactance $\mathbf{X_n}$ is

$$X_n = (\frac{n}{{n_0}^2 - 1} - \frac{n}{n^2 - 1}) \cdot \frac{1}{\omega c} \tag{6}$$

The curve of reactance $\mathbf{X_n}$ versus harmonic order $\mathbf{n}$ is shown in Fig. 4, which shows that

$\mathbf{n = 1 \Rightarrow X_n = \infty}$

$\mathbf{1 < \boldsymbol{n} < \boldsymbol{n_0} \Rightarrow X_n < 0}$ (capacitive)

$\mathbf{n = n_0 \Rightarrow X_n = 0}$

$\mathbf{n > \boldsymbol{n_0} \Rightarrow X_n > 0}$ (inductive)

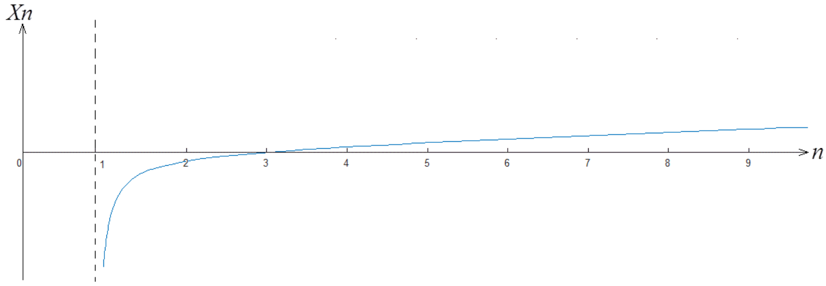

Fig. 4. The curve of the reactance X_n versus harmonic order $n(n_0=3)$

2) Impedance variation of the filter due to design parameter deviation.
For convenience, the following two assumptions are introduced.
Firstly, the inner resistance of condenser $\mathbf{C}$and reactor $\mathbf{L_p}$ is zero.
Secondly, equivalent resistance R is not affected by frequency.
This implies that the skin effect of the conductor is not taken into account.
Under the above assumptions, the n-th harmonic impedance of the filter can be written as

$$Z_n = Z_{s,n} + Z_{p,n} \tag{7}$$

where $\mathbf{Z_{s,n}}$ is the n-th harmonic impedance of serial branch (R,$\mathbf{L_s}$); $\mathbf{Z_{p,n}}$ is the n-th harmonic impedance of parallel branch(C//$\mathbf{L_p}$).

$\mathbf{Z_{s,n}}$ and $\mathbf{Z_{p,n}}$ can be derived from the follows.

$$Z_{s,n} = R + jX_{s,n} \tag{8}$$

$$\frac{1}{Z_{p,n}} = \frac{1}{-jX_{c,n}} + \frac{1}{jX_{p,n}} \tag{9}$$

where $\mathbf{X_{s,n}}$ is then-th harmonic impedance of serial reactor $\mathbf{L_s}$; $\mathbf{X_{c,n}}$ is the n-th harmonic impedance of condenser C; $\mathbf{X_{p,n}}$ is the n-th harmonic impedance of parallel reactor $\mathbf{L_p}$.

From the equation (9)

$$Z_{p,n} = j\frac{X_{c,n} \cdot X_{p,n}}{X_{c,n} - X_{p,n}} \tag{10}$$

In the above equations, $\mathbf{X_{s,n}}$, $\mathbf{X_{p,n}}$, $\mathbf{X_{c,n}}$ are as follows.

$$X_{s,n} = n\omega L_s \tag{11}$$

$$X_{p,n} = n\omega L_p \tag{12}$$

$$X_{c,n} = \frac{1}{n\omega c} \tag{13}$$

Assuming that the values of design parameters are $\mathbf{f}^*$, $\mathbf{L_s}^*$, $\mathbf{L_p}^*$, $\mathbf{C}^*$, $\mathbf{R}^*$ and their relative deviations are $\boldsymbol{\delta_f}$, $\boldsymbol{\delta_s}$, $\boldsymbol{\delta_p}$, $\boldsymbol{\delta_c}$, $\boldsymbol{\delta_R}$, then

$$\delta_f = \frac{\Delta f}{f^*}, \quad \delta_s = \frac{\Delta L_s}{{L_s}^*}, \qquad \delta_p = \frac{\Delta L_p}{{L_p}^*}, \delta_c = \frac{\Delta C}{C^*}, \delta_R = \frac{\Delta R}{R^*} \tag{14}$$

where
$\mathbf{\Delta f}$: the deviation of the fundamental frequency
$\mathbf{\Delta L_s}$: the deviation of the reactance of serial reactor LS
$\mathbf{\Delta L_p}$: the deviation of the reactance of parallel reactor LP
$\mathbf{\Delta C}$: the deviation of the capacitance of condenser C
$\mathbf{\Delta R}$: the deviation of the equivalent resistance of R
Considering

$$\omega = 2\pi f^*(1+\delta_f), \quad L_s = {L_s}^*(1+\delta_s), \qquad L_p = {L_p}^*(1+\delta_p), \qquad C = C^*(1+\delta_c) \tag{15}$$

then Equations (11), (12) and (13) can be written as:

$$\mathrm{X}_{s,n} = n \cdot 2\pi f^* L_s^* (1+\delta_f)(1+\delta_s) \tag{16}$$

$$\mathrm{X}_{p,n} = n \cdot 2\pi f^* L_p^* (1+\delta_f)(1+\delta_p) \tag{17}$$

$$\mathrm{X}_{c,n} = \frac{1}{n \cdot 2\pi f^* c_0 (1+\delta_f)(1+\delta_c)} \tag{18}$$

Considering

$$X_{s0} = 2\pi f^* L_s^*, \quad X_{p0} = 2\pi f^* L_p^*, \quad X_{c0} = \frac{1}{2\pi f^* c_0}$$

and neglecting the 2nd order terms, then

$$X_{s,n} = nX_{s0}(1+\delta_f+\delta_s) \tag{19}$$

$$X_{p,n} = nX_{p0}(1+\delta_f+\delta_p) \tag{20}$$

$$X_{c,n} = \frac{X_{c0}}{n \cdot (1+\delta_f+\delta_c)} \tag{21}$$

Substituting $R = R^*(1+\delta_R)$ and equation (19) into equation (8),

$$\mathrm{Z}_{s,n} = R^*(1+\delta_R) + jn(1+\delta_f+\delta_s)\mathrm{X}_{s0} \tag{22}$$

Substituting equations (20), and (21) into equation (10),

$$\mathrm{Z}_{p,n} = \frac{\frac{\mathrm{X}_{c0}}{n(1+\delta_f+\delta_c)} \cdot n\mathrm{X}_{p0}(1+\delta_f+\delta_\mathrm{p})}{\frac{\mathrm{X}_{c0}}{n(1+\delta_f+\delta_c)} - n\mathrm{X}_{p0}(1+\delta_f+\delta_\mathrm{p})} \tag{23}$$

From the resonance condition,

$$X_{c,0} = X_{p0} \tag{24}$$

Substituting equation (24) into equation (23) and arranging,

$$\mathrm{Z}_{p,n} = j\frac{n(1+\delta_f+\delta_\mathrm{p})}{1-n^2(1+2\delta_f+\delta_\mathrm{p}+\delta_c)}\mathrm{X}_{c0} \tag{25}$$

Substituting equations (22), (25) into equation (7),

$$Z_n = R_0(1+\delta_R) + j[n(1+\delta_f+\delta_s)X_{s0} + \frac{n(1+\delta_f+\delta_p)}{1-n^2(1+2\delta_f+\delta_p+\delta_c)}X_{c0} \tag{26}$$

As the impedance of filter is zero at the n_0-th order harmonic frequency,

$$jn_0X_{s0} + \frac{jn_0X_{p0}(-j\frac{X_{c0}}{n_0})}{jn_0X_{p0} - j\frac{X_{c0}}{n_0}} = 0 \tag{27}$$

Thus

$$X_{c0} = ({n_0}^2 - 1)X_{s0} \tag{28}$$

Substituting equation (28) into equation (26),

$$Z_n = R_0(1+\delta_R) + j\left[(1+\delta_f+\delta_s) - \frac{(1-{n_0}^2)(1+\delta_f+\delta_p)}{1-n^2(1+2\delta_f+\delta_p+\delta_c)}\right]nX_{s0} \tag{29}$$

A parameter ξ_n affected by harmonic order and design parameter deviation is introduced as follows:

$$\xi_n = \frac{n}{n_0}\left[(1+\delta_f+\delta_s) - \frac{(1-{n_0}^2)(1+\delta_f+\delta_p)}{1-n^2(1+2\delta_f+\delta_p+\delta_c)}\right] \tag{30}$$

If the quality factor of serial branch at the n_0-th order harmonic frequency is denoted as q_{n0}, then

$$q_{n0} = \frac{n_0 X_{s0}}{R_0} \tag{31}$$

Substituting equations (30), (31) into equation (29),

$$Z_n = [\frac{(1+\delta_R)}{q_{n0}} + j\xi_n]\, n_0 X_{s0} \tag{32}$$

For further consideration of ξ_n that reflects the main characteristics of the filter, the parameters $\delta_1, \delta_2, \delta_3$ are introduced as follows:

$$\delta_1 = \delta_f + \delta_s \ \ , \delta_2 = \delta_f + \delta_p \ , \delta_3 = 2\delta_f + \delta_p + \delta_c$$

Then the equation (30) is derived as

$$\xi_n = \frac{n}{n_0}[(1+\delta_1) - \frac{(1-{n_0}^2)(1+\delta_2)}{1-n^2(1+\delta_3)}] \tag{33}$$

There are the following two special cases depending on the harmonic order n.

Case 1: When n=1(fundamental frequency),

$$\xi_1 = \frac{1}{n_0}\left[\frac{(1+\delta_1)\delta_3 + (1-{n_0}^2)(1+\delta_2)}{\delta_3}\right] \tag{34}$$

Considering that $n_0^2 \gg 1$, $\delta_1 \ll 1$, $\delta_2 \ll 1$, $\delta_3 \ll 1$, then

$$\xi_1 = -\frac{n_0}{\delta_3} \tag{35}$$

Substituting equation (35) into equation (32) and considering $q_{no} \gg 1$, then

$$Z_1 = -\mathrm{j}\frac{n_0^2}{\delta_3}X_{s0} = -j\frac{n_0^2}{2\delta_f + \delta_p + \delta_c}X_{s0} \tag{36}$$

Case 2: When $n = n_0$ (the harmonic order to be removed),

$$\xi_{n0} = (1+\delta_1) - \frac{(1-{n_0}^2)(1+\delta_2)}{1-{n_0}^2(1+\delta_3)} \tag{37}$$

Considering $n_0^2 \gg 1$ and $\delta_1 \cdot \delta_3 \approx 0$, then

$$\xi_{n0} = \delta_1 + \delta_3 - \delta_2 = 2\delta_f + \delta_s + \delta_c \tag{38}$$

Substituting equation (35) into equation (32) and considering $\delta_R \ll 1$,

$$Z_{n_0} = [\frac{1}{q_{no}} + \mathrm{j}\big(2\delta_f + \delta_s + \delta_c\big)]n_0 X_{s0} \tag{39}$$

Equations (36) and (39) show that the filter has the best quality under the condition of $\delta_s + \delta_c = 0$ and $\delta_p + \delta_c = 0$, because δ_f varies continuously depending on the power system.

$\delta_s + \delta_c = 0$ is the best filtering condition, while $\delta_p + \delta_c = 0$ is the condition of least change of the fundamental power factor.

That is why the following procedure is necessary for composing the best filter:

To measure the capacitance of the condenser

To calculate the deviation δ_c and its direction

To regulate the serial reactor so as to be $\delta_s = -\delta_c$

To regulate the parallel reactor so as to be $\delta_p = -\delta_c$

3. Simulation

Simulations of the below-shown three circuits below were carried out using MATLAB Simulink.

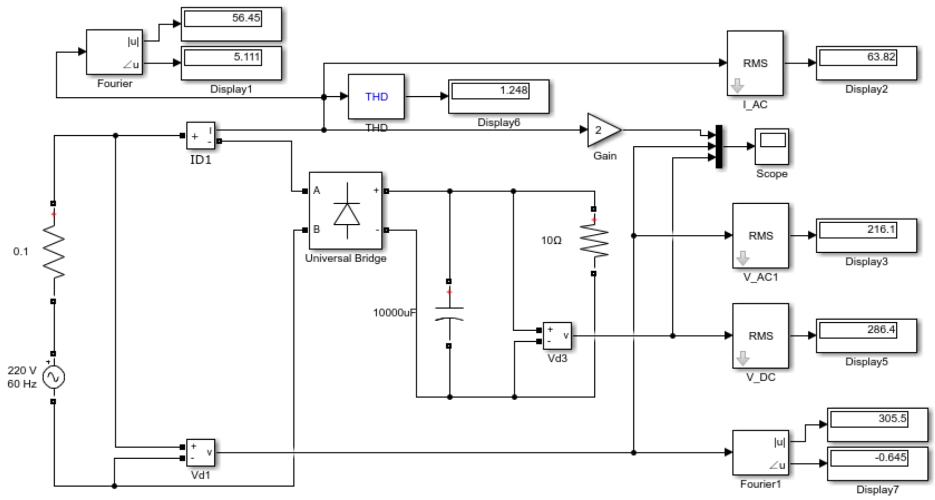

Figure 5. Single-phase rectifier without filter.

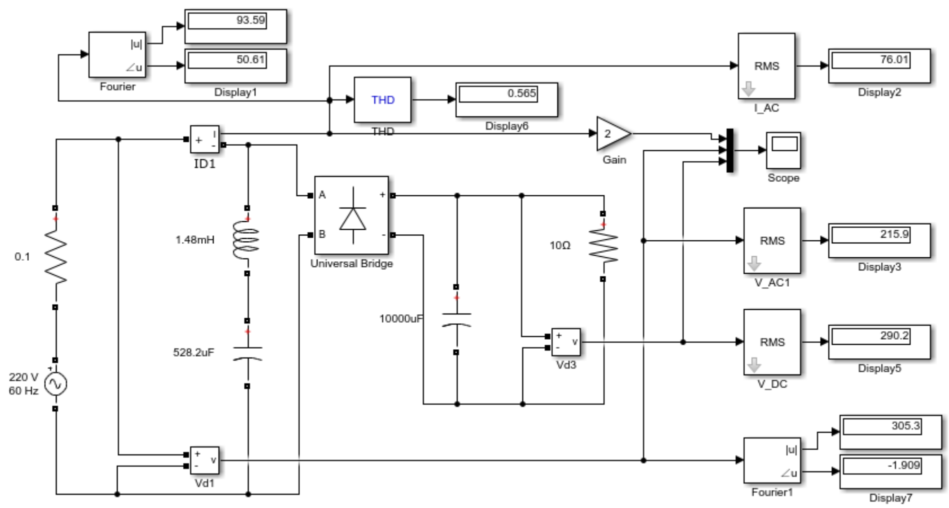

Figure 6. Single phase rectifier with the conventional single-tuned 3rd-order harmonic filter.

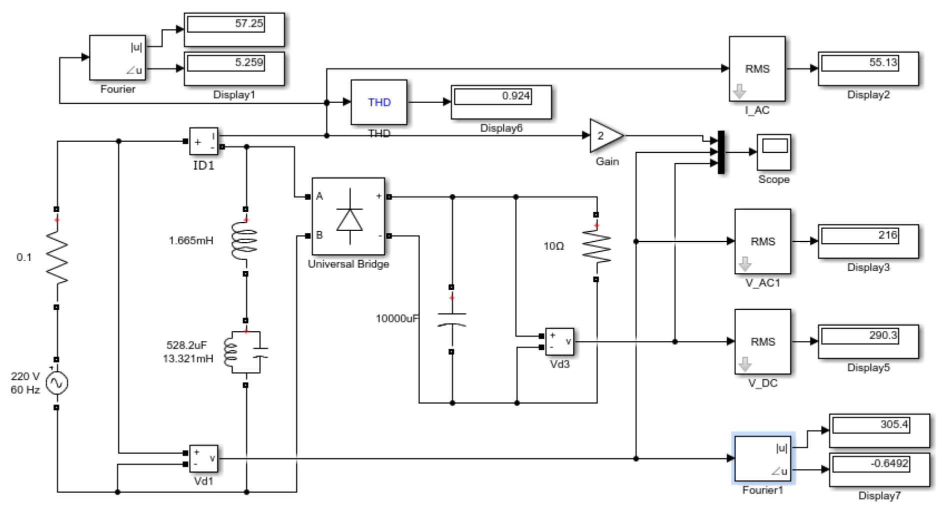

Figure 7. Single phase rectifier with novel single-tuned 3rd order harmonic filter.

The results obtained from the simulation of these three circuits are shown in Fig. 8-Fig. 10 and Table 1-Table 2.

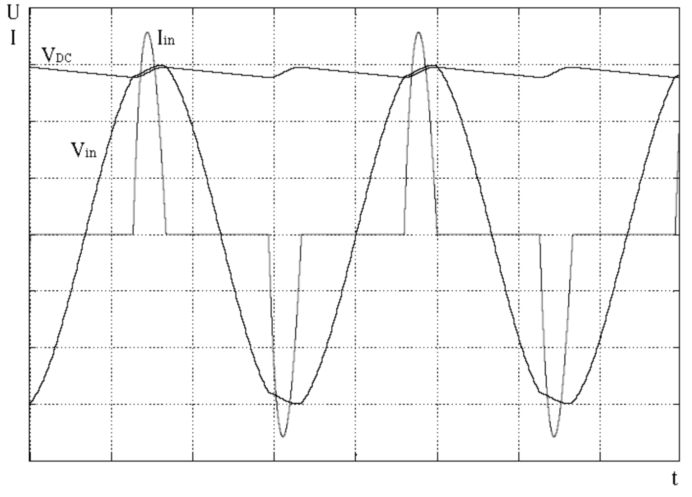

Figure 8. Scope waves without filter.

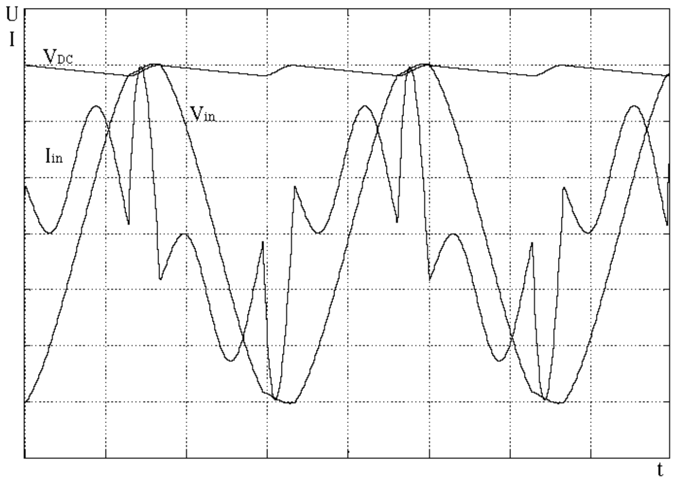

Figure 9. Scope waves with the conventional filter.

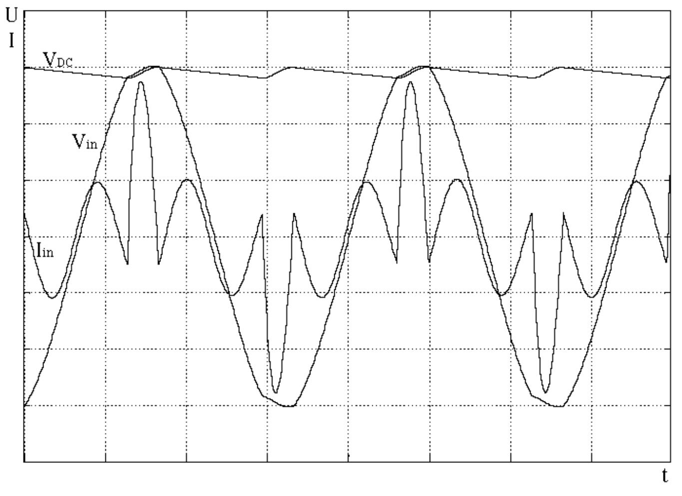

Figure 10. Scope waves with novel filter.

Table 1. Main parameters of three circuits

No.	Filter	I_{rms} (A)	I_1 (A)	φ_1 (°)	THD_i (%)	U_{DC} (V)	P_{loss} (%)	I_h (A)	P (kW)
1	none	63.82	56.45	5.76	124.8	286.4	1	70.45	8.20
2	conventional	76.01	93.59	52.52	56.5	290.2	1.42	52.88	8.42
3	novel	55.13	57.25	5.91	92.4	290.3	0.75	52.90	8.43

where

I_{rms}: the rms value of input current

I_1: the amplitude of input fundamental current

φ_1: the phase difference between input fundamental voltage and current

THD_i: the total harmonic distortion of input current

U_{DC}: the voltage of DC side

P_{loss}: the ratio of transmission loss compared to that of no filter

$$P_{loss} = \left(\frac{I_{rms}}{I_{rms,none}}\right)^2 \tag{40}$$

where $I_{rms,none} = 63.82$

I_h: the total harmonic quantity of input current

$$I_h = THD_i \times I_1 \tag{41}$$

P: the power of the load

$$P = \frac{{U_{DC}}^2}{R} \tag{42}$$

where R=10

Table 2. Harmonic current amplitude of three circuits

No.	**Filter**	**I_1 (A)**	**I_2 (A)**	**I_3 (A)**	**I_4 (A)**	**I_5 (A)**	**I_6 (A)**	**I_7 (A)**	**I_8 (A)**	**I_9 (A)**	**I_{10} (A)**
1	none	56.5	0	50.1	0	39	0	25.7	0	13.0	0
2	conventional	93.6	0	0.4	0	40.8	0	28.0	0	15.4	0
3	novel	57.3	0.3	0.5	0.3	40.8	0.2	28.0	0.1	15.4	0.1
No.	**Filter**	**I_{11} (A)**	**I_{12} (A)**	**I_{13} (A)**	**I_{14} (A)**	**I_{15} (A)**	**I_{16} (A)**	**I_{17} (A)**	**I_{18} (A)**	**I_{19} (A)**	**I_{20} (A)**
1	none	3.7	0	3.6	0	5.1	0	4.0	0	1.7	0
2	conventional	5.4	0	2.6	0	4.9	0	4.6	0	2.6	0
3	novel	5.3	0.1	2.7	0.1	4.9	0.1	4.6	0	2.6	0.1

where I_i is the i-th order harmonic current amplitude.

From Table 1 and Table 2, the following can be concluded:

(1) Novel single-tuned harmonic filter can reduce the transmission loss to approximately 0.53 times compared to the conventional one.

The conventional single-tuned filter drastically changes the phase difference between the input fundamental voltage and current while filtering, thereby increasing the transmission loss by 1.42 times compared to the absence of the filter.

However, the novel single-tuned filter does not change the phase difference, so it can reduce the transmission loss by 0.75 times compared to the absence of the filter.

Thus, comparing the two filters with each other, it can be seen that the novel filter can reduce the transmission loss by 0.53 times compared to the conventional one.

(2) Filtering capacity of the novel single-tuned harmonic filter is the same as that of the conventional one.

Total and individual harmonic quantities are nearly the same in those two cases.

4. Conclusion

In this paper, the characteristics of a new type of single-tuned harmonic filter have been considered, which acts only as a harmonic filter, but does not allow the fundamental current to flow through it and does not change the fundamental power factor. Using this filter makes it possible to reduce the transmission loss considerably at the input side while keeping the same filtering effect as the conventional one. Through simulations, the advantages of the novel filter have been ascertained.

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